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Business cycles, fossil energy and air pollutants: U.S. "stylized facts"

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ABSTRACT

This paper, in its exploratory nature, develops a descriptive empirical analysis which tries to capture the "regularities" underlying the relationship between the economy, fossil energy use and anthropogenic air pollutants at business cycle frequency. The analysis uses as framework the economy of the United States in the period 1990–2019. The results are organized in terms of "stylized facts" which, in their essential nature, provide a rough idea of the cyclical interactions between the variables of interest. In addition to this, they also act as a benchmark to assess how well theoretical macroeconomic models are able to mimic the reality. A first result is the relatively high volatility characterizing both fossil energy use and air pollutants with respect to the business cycle. A second result is the moderately high procyclicality between fossil energy use, in particular oil, and the business cycle. Among air pollutants, CO_2 and CO share a moderately high level of procyclicality. With few exceptions, the other pollutants are only weakly associated with the business cycle.

1. Introduction

The production process, at its core, consists in the mere transformation of inputs into outputs (Hennings, 1990). Within an ecological economic framework, however, a few additional details are worth consideration: given a certain level of technology, the use of fossil energy sources as factors of production implies, together with the creation of goods and services, the discharge of certain amounts of wastes into natural sinks such as water, soil and air. Those wastes belonging to the latter category, in particular, are called air or atmospheric pollutants and, together with fossil energy sources, represent the main object of this article. Indeed, in its exploratory and descriptive nature, this work employs the United States economy as the framework to shed light on the "regularities" between aggregate output, fossil energy use and atmospheric pollutants at business cycle frequencies. This is achieved by compiling the *stylized facts* of the economy, that is, a set of summary statistics which capture the salient features of economic fluctuations and act as the empirical benchmark to establish how well theoretical macroeconomic models mimic the reality (Canova, 1998).

Environmental, social and corporate governance (ESG) criteria constitute a micro-oriented framework with the aim to foster real changes towards sustainable practices. Indeed, relevant targets such as GHG emissions, air pollutants and energy consumption are included within the ESG's environmental dimension (Li et al., 2021). Activities like production and waste discharge are carried out by single economic agents such as households and firms; the sum of these actions, however, may result in phenomena which can be of interest at the aggregate level. No clear-cut evidence exists regarding the impact ESG investments have on macro-financial variables, in that the research in this specific field is still at its early-stage and, thus, relatively incomplete (Zhang et al., 2021).

Similarly, the number of macroeconomic works empirically addressing the link between the business cycle, fossil energy use and air pollutants is relatively low. The vast majority of them, being developed within the field of climate change economics, concentrates almost exclusively on carbon dioxide alone. Focusing on the United States economy, Heutel (2012) establishes a procyclical and inelastic relationship between the cyclical components of CO_2 emissions and GDP. Sheldon (2017), sticking with the U.S. framework, adds that this relationship is asymmetrical: while rises in GDP are accompanied by very modest increases in CO_2 emissions, a decline in the former is usually followed by a deeper fall in the latter. In other words, CO_2 shows almost inelastic behaviour with respect to rises in GDP and elastic behaviour when GDP falls. Extending the geographical domain by means of a cross-country panel, Doda (2014) finds that GDP and carbon dioxide are procyclical during booms and busts, this characteristic becoming more evident in the case of wealthy countries. It also emerges that GDP is in general less volatile than CO_2 emissions, this last aspect being especially rooted in the context of poor countries.

The act of uncovering empirical regularities and collect them in the form of stylized facts is well established in the macroeconomic literature. Among the most important examples of this approach fall corner-

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stones such as Stock and Watson (1999) and King and Rebelo (1999). Despite its usefulness in providing cues about the mutual behaviour of aggregate variables at business cycle frequencies, this basic descriptive practice remains relatively overlooked within the macro-environmental field. As a recent example of environmental flavour, Sarwar et al. (2021) captured some stylized facts between GDP and emissions concentrating on countries of South Asia. This work tries to extend the use of stylized facts from the mere economic realm to fossil energy use and air pollutants. It does not limit itself to CO_2 alone and targets the U.S. context, this latter representing, for its importance, the macroeconomic benchmark among modern industrial economies. To the best of the author's knowledge, such an analysis has not been developed in the literature before.

The remainder of the paper is organized as follows. Section 2 gives a brief overview of the main features characterizing those fossil energy sources and air pollutants considered throughout the work. Section 3 provides information about the data used in the work and the way they are manipulated in order to extract the cyclical components. Section 4 supplies a detailed description of the results emerging from this descriptive analysis. Section 5 provides the main conclusions of the study. The Appendix at the end of the paper collects additional information concerning the data employed throughout the work.

2. Background on fossil fuels and air pollutants

2.1. Fossil fuels

From a *biohistorical* perspective, the economic phenomenon has mainly been a tale of increasing energy consumption. In order to sustain the day-by-day growing number of technological processes characterizing their societies, humans have relied only in minimal part on *somatic* energy, i.e., the one acquired from food and exerted through muscles. Instead, most energy has been of the *extra-somatic* kind, i.e., generated by sources foreign to human metabolism (Boyden and Dovers, 1992). In fact, starting back to at least 250,000 years ago with the control of fire for cooking purposes, the exploitation of extra-somatic energy sources has been characterized by several stages of development, which culminated in the transition from the early burning of biomass like wood or agricultural residues to the combustion of fossil fuels such as coal, oil, and gas (Smil, 2004).

There is no doubt fossil fuels have contributed in generating the high standard of living enjoyed by developed countries such as the United States. The rationale behind this achievement can be explained in terms of fossil fuels' ability to replace large quantities of human labour at relatively low prices (Pimentel and Pimentel, 2007, p. 43). At the same time, the burning of fossil fuels is recognized to represent a fundamental source of air pollutants (Holman, 1999). More specifically, the emission in massive quantities of air wastes contributes to a plethora of phenomena which, ranging from individual respiratory problems to *global warming*, have the potential to impact on many aspects of human life also in dramatic ways (Armaroli and Balzani, 2011).

Despite the reiterated anathemas against fossil fuels, their abandonment seems far from being achievable at least in the nearest future. In reality, from an economic point of view, the relationship between energy and GDP is still not fully understood: while no conclusive evidence exists regarding whether energy determines growth or *vice versa*, mainstream economics tends to undervalue the role of energy despite its positive correlation with output (Stern, 2018). With reference to United States, Fig. 1 plots the changes in real GDP and fossil energy use for the period 1990–2019 using 1990 as the reference year. In general, the main fossil energy aggregate displays a flatter growth than real GDP. Oil use tends to follow a relatively stable path, sticking sufficiently close to the main fossil energy aggregate. Coal shows a sharp decline in its consumption path, this latter being driven by the waning in the use of coal for electricity generation. On the contrary, gas has seen an increasing employment in its use with respect to 1990, the last decade being characterized by a relatively steep growth. Recent projections suggest United States will experience new peaks in the production of fossil fuels[1] in 2023 as well as a growth in CO_2 emissions[2] in the period 2022–2023. More in general, despite the increasing interest in renewable energy, United States consumption of fossil sources, mainly oil and natural gas, is expected to rise through year2050.[3]

2.2. Air pollutants

Awareness concerning the threat air pollution poses on human health can be traced back to ancient times. The general idea that environmental quality affects human bodies was early discussed by the Greek physician Hippocrates in his work *Airs, Waters, Places* (400 B.C.) (Littré et al., 1881). In his *Letter 104 to Lucilius* (61 A.D.), Seneca, Roman statesman and philosopher, perceived an improvement in his health conditions once he escaped from "*the oppressive atmosphere*" of Rome and "*that reek of smoking cookers which pour out, along with a cloud of ashes, all the poisonous fumes they've accumulated in their interiors whenever they're started up*" (Campbell, 1969, p. 185).

Moving on to more recent times, research has acknowledged the direct and indirect detrimental effects of air pollutants on human health, blaming them as an important cause of illness and death (Chen et al., 2007b). Huge amounts of carbon, captured within fossil fuels and stored underground for millions of years, have been abruptly released in the atmosphere in the form of *carbon dioxide* (CO_2) a by-product of fossil combustion. Anthropogenic CO_2 emissions, mainly caused by the burning of fossil fuels for energy production, have been identified as the major direct contributor to the phenomenon of *global warming*, that is, the long-term increase in Earth's overall temperatures, and of the more general phenomenon of *climate change*. Despite the relatively poor understanding of the complex mechanisms underlying this occurrence, its potential effects on human health range from short-term increases in mortality due to heat waves to the rise of infectious diseases such as dengue or malaria (Kurane, 2010). The list of atmospheric wastes which originate from the burning of fossil fuels does not limit itself to carbon dioxide only. Many other compounds, acting on more or less circumscribed geographical areas, are able to directly harm the health of those persons that are exposed to them.

Carbon monoxide (CO), whose discharge is mainly ascribed to the incomplete combustion of fossil fuels in the transportation sector, acts as an indirect contributor to global warming. On a conceptual level, the mechanism is relatively simple: CO reacts with specific compounds that would otherwise lead to the destruction of methane and ozone, two of the most important greenhouse gases after CO_2, thereby indirectly boosting their atmospheric concentrations. The consequences of CO intoxication in closed environments are well established and include cardio-pulmonary diseases which can end with fatal outcomes. CO's direct effects on human health due to outdoor exposure are more difficult to determine (Chen et al., 2007a).

Nitrogen oxides (NO_x) are a large family of gases, whose emission is mostly caused by stationary fuel combustion and transportation (Kampa and Castanas, 2008). Valued in terms of potential dangers to human health, nitrogen dioxide (NO_2) represents the most emblematic compound among NO_x. In closed places, NO_2 can lead to severe respiratory

[1] U.S. Energy Information Administration (EIA), EIA expects U.S. fossil fuel production to reach new highs in 2023. https://www.eia.gov/todayinenergy/detail.php?id=50978 (accessed June 20, 2022).

[2] U.S. Energy Information Administration (EIA), EIA expects U.S. energy-related carbon dioxide emissions to increase in 2022 and 2023. https://www.eia.gov/todayinenergy/detail.php?id=50958 (accessed June 20, 2022).

[3] U.S. Energy Information Administration (EIA), EIA projects U.S. energy consumption will grow through 2050, driven by economic growth. https://www.eia.gov/todayinenergy/detail.php?id=51478 (accessed June 20, 2022).

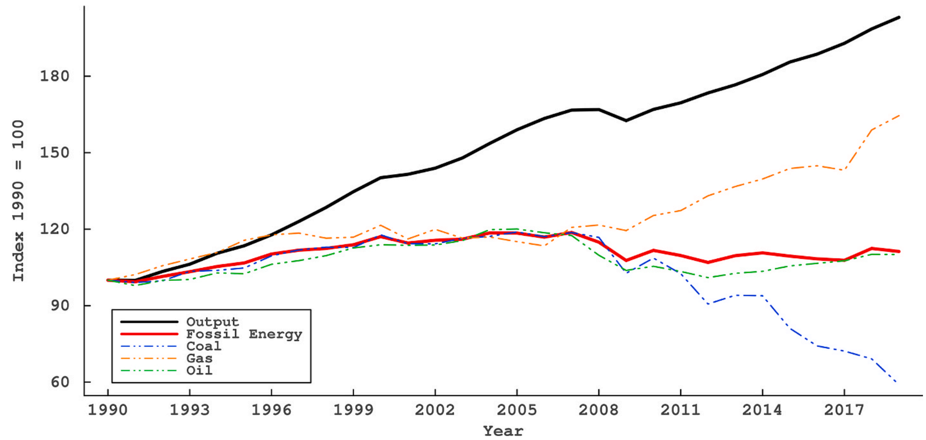

Fig. 1. Fossil Energy Use vs GDP.

problems and even fatal outcomes. Data about the effects of outdoor exposure to NO_2 are relatively inconsistent and mainly associated with respiratory symptoms like asthma (Chen et al., 2007a).

Emissions of *sulfur dioxides* (SO_2) in the atmosphere are caused by the burning of fossil fuels, mostly coal, containing high levels of sulfur. With respect to human health, sulfur dioxide behaves as an irritant of the respiratory tract, whose consequences can be serious in case of exposure to high concentrations (Chen et al., 2007a). From the environmental point of view, SO_2 as well as NO_x emissions play a very relevant role in contributing to the formation of acid rains and acid fogs. These phenomena can harm ecosystems in many different ways. Among them, acid rains may lead to the acidification of waters and are able to damage forests by harming their foliage.

Volatile organic compounds (*VOC*) are chemical species of organic nature that easily volatilize, i.e., evaporate, at room temperature. The risk of exposure to *VOC* is high within domestic walls. This can happen either due to specific household products already present in confined spaces or when emissions from outdoor sources such as vehicle and industrial plants penetrate into buildings (Rumchev et al., 2007). Given their highly heterogeneous nature, inhalation can result in a plethora of different symptoms which ranges from respiratory to haematological problems. Some VOC are classified as carcinogenic (Kampa and Castanas, 2008).

Agricultural sector represents one of the principal generators of *ammonia* (NH_3) emissions. Wastes from farming due to high-protein feed and NH_3-based fertilizers are among the major contributors. Significant levels and long exposure to indoor ammonia can impact animals by reducing their body weights. They also affect human health with symptoms such as eye and lung irritations. Deposition of outdoor ammonia on waters and surfaces can have detrimental effects on aquatic species and soil cultures (Gay and Knowlton, 2005).

Particulate matter are mixtures of solid and liquid particles which can be found in the air. Depending on the source of emission, they can vary in terms of size and composition. Particulate pollutants are usually categorized into two groups. PM_{10} have diameter smaller or equal to 10 μ m; $PM_{2.5}$, instead, are ultra-fine compounds characterized by a maximum diameter of 2.5 μ m. The danger attached to particulate matter is inversely proportional to the size of the particles. In other words, the lower the size, the higher their ability to penetrate and deposit into the lower airways, thereby causing harm (Kim et al., 2015). People exposed to outdoor air pollution due to particulate matter are at higher risk of developing cardiopulmonary diseases and lung cancer (Chen et al., 2007c}.

Focusing on the United States economy, Fig. 2 describes how the changes in GDP and air pollutants evolved over the period 1990–2019 with respect to year 1990. Despite United States GDP keeps growing over time, all atmospheric pollutants, independent of their nature, tend to shrink at different degrees. Of interest is the behaviour of SO_2 emissions, whose decline appears to be particularly sharp over time. This peculiar result can be partially explained in light of the Acid Rain Plan, that is, one of the Amendments made in year 1990 to the U.S. Clean Air Act, this latter representing the main legislation currently targeting air pollutants at federal level. The Acid Rain Plan is a program which seeks to implement an increasingly stringent upper limit on emissions of SO_2 and NO_x. Comparing Fig. 2 with Fig. 1 it is worth to notice that the decrease in SO_2 has gone hand in hand with the decline in use of coal as energy source.

3. Material and methods

3.1. Data

The dataset includes observations about the United States economy, the use of fossil energy and those air pollutants originating from anthropogenic activities. It covers a time span of 30 years, from 1990 to 2019. At the lower end, the dataset is limited by the availability of air pollution series, which start from year 1990. On the upper end, the most recent year of the series has been restricted to 2019 in order to elude the impact of Covid-19 outbreak and, thus, its extraordinary and potentially disruptive consequences on economic (Thorbecke, 2020; Li et al., 2022) as well as atmospheric variables (Le Quéré et al., 2020; Kroll et al., 2020). Economic data, observations on fossil energy use and *carbon dioxide* (CO_2) emissions are potentially available at monthly or quarterly frequency; however, given the nature of all remaining series concerning air pollutants, homogeneity among observations has suggested to shape the dataset at yearly frequency.

Output, namely Gross Domestic Product (GDP), represents the only macroeconomic series used throughout this work. Its inclusion is fundamental, in that it is usually adopted as proxy for the overall business cycle. It can be easily retrieved from Federal Reserve Economic Data (FRED) system. In line with business cycle literature, for the sake of the current analysis it is employed in real terms.[4]

Data regarding the use of fossil energy are organized so as to contemplate the main fossil aggregate as well as its components, namely *coal*, *gas*, and *oil*. The series can be accessed from the U.S. Energy Information Administration (EIA).

Observations concerning air pollutants can be split into two categories according to the specific agency which supplies them. Data on CO_2 emissions are available from the U.S. Energy Information Administration (EIA). On the other hand, all remaining series concerning air

[4] Nominal GDP is converted to real GDP by means of the Implicit Price Deflator (IPD).

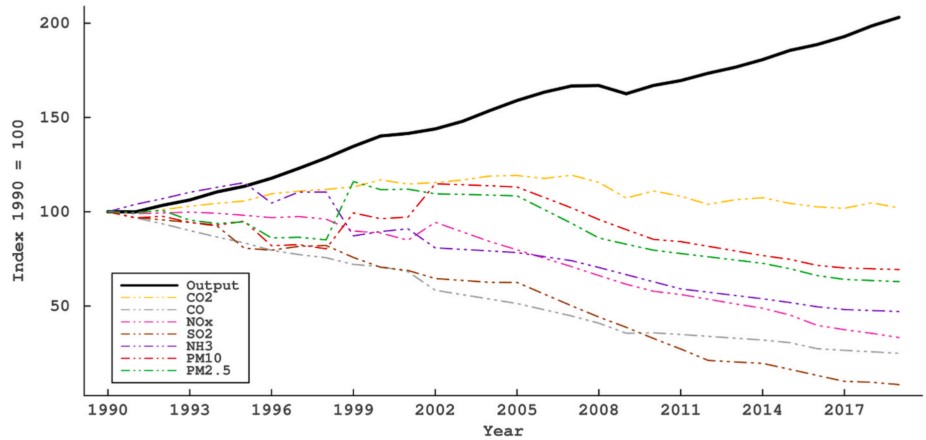

Fig. 2. Atmospheric Pollutants vs GDP.

pollutants are supplied by the U.S. Environmental Protection Agency (EPA).

Among them, many classical gaseous pollutants are found, such as *carbon monoxide* (*CO*), *sulfur dioxide* (SO_2), *nitrogen oxides* (NO_x), *volatile organic compounds* (*VOC*), and *particulate matter* in the shape of PM_{10} and $PM_{2.5}$. Despite their potential relevance, the actual unavailability of series about ground-level *ozone*, persistent organic pollutants like *dioxins*, and heavy metals such as *lead* does not allow their inclusion within this analysis.

Except for CO_2, which is considered only at aggregate level, each pollutant is also analysed in terms of three[5] disaggregated macro-components: *stationary fuel combustion* sources, such as electric utilities; *industrial* sources, which include chemical, metal, and solvent utilization processes; *transportation* sources, which encompass the activity of both highway and off-highway vehicles.

Additional information about data is contained in the Appendix at the end of the paper.

3.2. Filter

At its core, empirical business cycle analysis requires to identify and extract the cyclical component of each economic aggregate of interest. In general, it is possible to decompose any time series v_t into a long-run non-stationary *trend* component τ_t and a short-run stationary *cyclical* component c_t, as described by Equation 1

$$v_t = \tau_t + c_t, t = 1, 2, \ldots, T \tag{1}$$

Upon this premise, the business cycle component c_t is extracted from v_t by means of the Hodrick-Prescott filter (HP-filter) (Hodrick and Prescott, 1997). This, together with a few other alternatives such as the Baxter-King filter (Baxter and King, 1999) or the Christiano-Fitzgerald filter (Christiano and Fitzgerald, 2003), is well established in the macroeconometric literature and, for this reason, is employed throughout this work. In formal terms, the HP-filter consists into solving the minimization problem described by Equation 2

$$\min_{\tau_t} \sum_{t=1}^{T} (v_t - \tau_t)^2 + \lambda \sum_{t=2}^{T-1} \left[(\tau_{t+1} - \tau_t) - (\tau_t - \tau_{t-1}) \right]^2 \tag{2}$$

which tells that the sum of the squared deviations of the distance between the actual series and its trend, i.e., the first term, is penalized by the sum of the squared second-order differences of the trend component, i.e., the second term. This is achieved by choosing a certain value of the smoothing parameter λ, which weights how much importance is placed to the changes in the trend. If λ is set equal to 0, the trend component coincides with the actual series. Increases in λ penalize variations in the growth rate of the trend; in particular, in the limit case of $\lambda \to \infty$ the trend component is constrained to exhibit a constant rate of growth. In other words, the higher λ, the stronger is the smoothing effect. For quarterly series, λ is conventionally set equal to 1600; however, in order to account for the annual frequency of the series, λ is adjusted to

$^{1600}/_{4^4} = 6.25$, as suggested by Ravn and Uhlig (2002). Once the trend extraction is achieved by implementing Equation (2), it is trivial to exploit Equation (1) to retrieve the cyclical component

c_t.

It is relevant to emphasize that each series, independent of its nature and prior to undergo any filtering process, is expressed in natural logarithmic terms. The application of linear filters like the HP-filter to actual time series, which are usually characterized by exponential growth, requires a log-transformations which almost guarantees the volatility of the series not to "explode". Each cyclical component is, thus, expressed as percent deviations from a trend. In this way, series characterized by heterogeneous natures are homogenized with respect to their measurement units, thereby enhancing their comparability.

4. Cyclical behaviours: results and discussion

Business cycles are broadly defined as recurrent fluctuations in economic activities (Cooley and Prescott, 1995). From a practical point of view, however, they are identified with the cyclical component of real aggregate output, which acts as the benchmark to compare co-movements between economic series across different sectors (Stock and Watson, 1999). In other words, real GDP is the key to operationalize the overall business cycle.

Let y_t denote the cyclical component of real output and x_t the cyclical component of any series considered in this work, including real output itself. This analysis exploits three moments to snap a shot of the main cyclical features of each variable under scrutiny: *pure standard deviations* $\sigma(x_t)$, which measure the amplitude of time series fluctuations in absolute terms; *relative standard deviations* $\sigma(x_t)/\sigma(y_t)$, which allow to compare the variability of each aggregate against output; *correlations* with output $\rho(y_t, x_{t+n})$, which measure the co-movements between output itself and any aggregate of interest at *n* years of distance. Any series which shows a strong and positive contemporaneous correlation with output is said to be procyclical with it; conversely, a variable behaves in countercyclical fashion when its contemporaneous correlation with output is large but negative. A weak correlation between any

[5] A fourth component could have been considered, which consists in intermittent, i.e., non-stationary, polluting sources. These encompass both natural processes, e.g., wild fires, and anthropogenic sources, e.g., the stabilization of dirt roads. The impossibility of discerning between these two categories for some class of pollutants, leads to the decision of excluding non-stationary polluting sources from the calculation of the national aggregate.

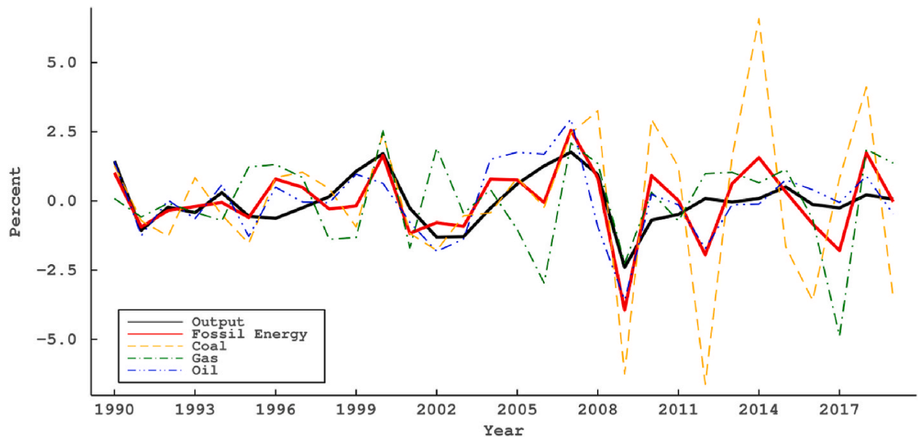

Fig. 3. Fossil Energy Use vs GDP.

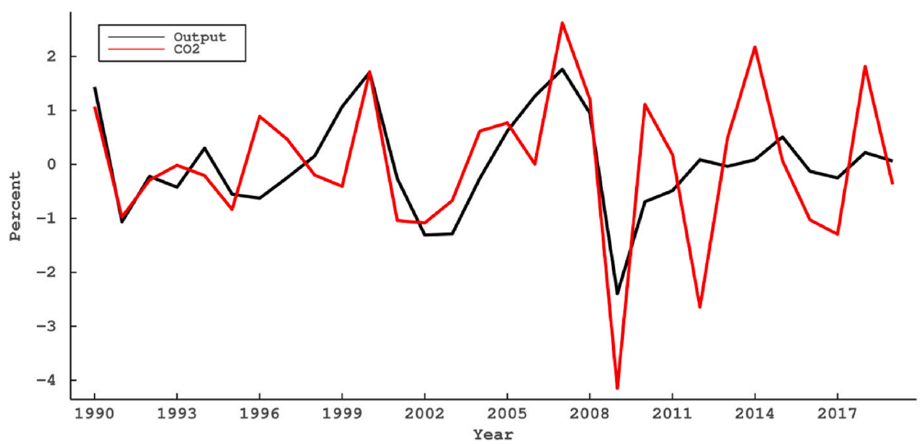

Fig. 4. Carbon Dioxide vs GDP.

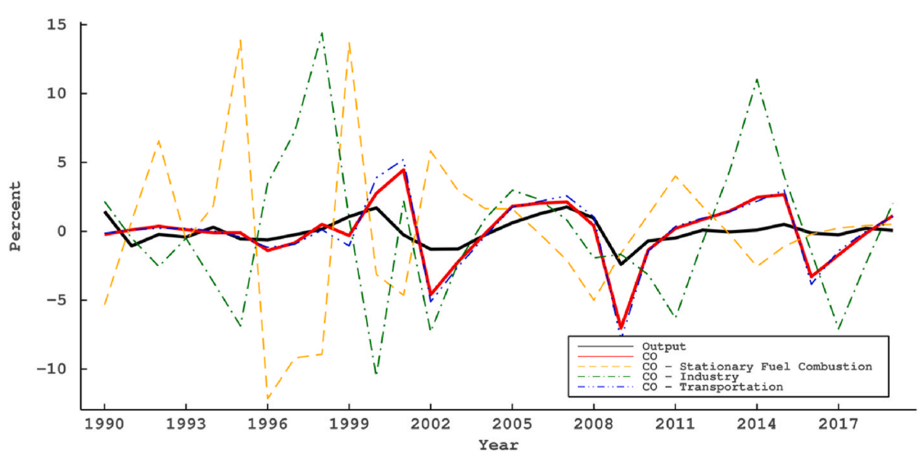

Fig. 5. Carbon Monoxide vs GDP.

variable and the business cycle is said to lead to an acyclical relationship between the two of them. Finally, a series is said to lead or lag the business cycle by n years if the highest correlation with y_t is reached, respectively, n years in advance ($n < 0$) or in delay ($n > 0$) from period t. As usual for a yearly setting, the correlation analysis is carried out including two leads and two lags.

A sequence of figures (Fig. 3, Fig. 4, Fig. 5, Fig. 6, Fig. 7, Fig. 8, Fig. 9 Figs. 10 and 11) is employed to present the results of this procedure. The goal is to enable a visual comparison of the cyclical behaviour of each series, no matter whether representing the main aggregate or its constituents, with the whole business cycle. The series have as unit percent deviations from trend. All salient features are collected within Table 1, which summarizes the above-mentioned stylized facts. These latter are listed starting from output, the benchmark variable, and gradually shifting towards fossil energy use and atmospheric pollutants.

The graphical representation of how fossil energy use and its components behave with respect to the business cycle is achieved by means of Fig. 3. All variables are mildly more volatile than real GDP; this can be

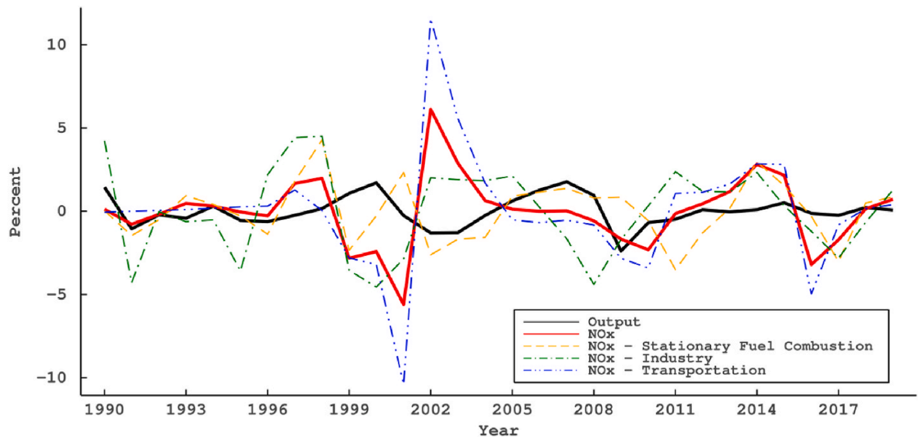

Fig. 6. Nitrogen Oxides vs GDP.

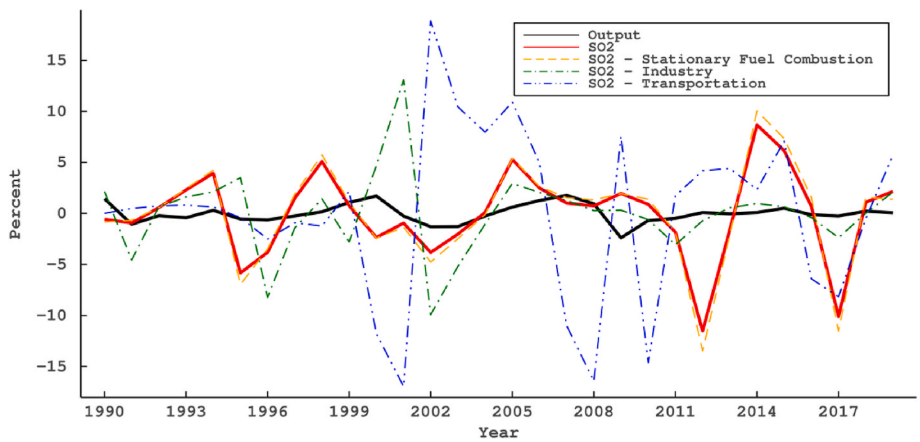

Fig. 7. Sulfur Dioxide vs GDP.

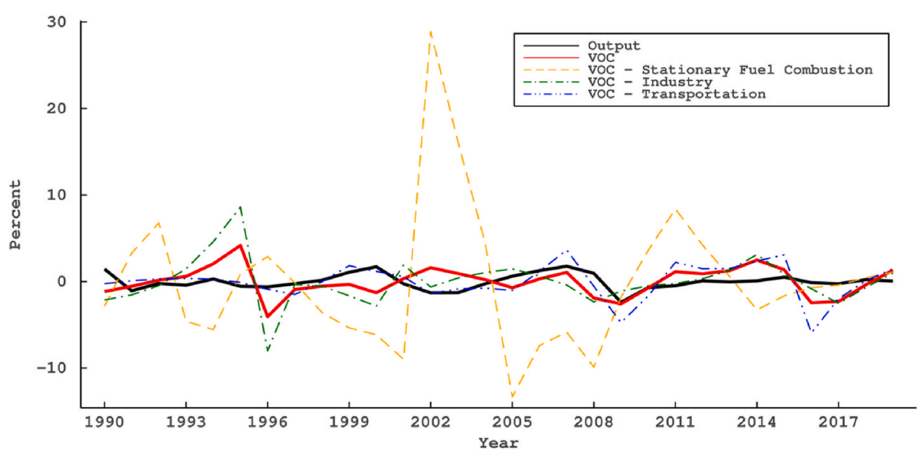

Fig. 8. Volatile Organic Compounds vs GDP.

easily recognized by looking at the energy use from coal. Table 1 suggests that aggregate fossil energy use, in all its shapes, is procyclical with the business cycle. In particular, the main aggregate is characterized by a moderately strong contemporaneous correlation with output (0.66). On the other hand, the strong contemporaneous correlation between energy use from oil and the business cycle (0.77) suggests a good degree of positive synchronization of the two variables. Coal use and gas use are weakly correlated with the business cycle. On the whole, the moderately high procyclical behaviour the main aggregate and oil use display with respect to the overall business cycle reinforces the intuition that a certain degree of association exists between fossil energy use and the production process.

The analysis of air pollutants starts by considering the case of CO_2 emissions, whose cyclical behaviour with respect to real output is graphically captured in terms of Fig. 4. Carbon dioxide emissions appear to be slightly more volatile than the business cycle. Table 1 corroborates these visual results by presenting a relative standard deviation between CO_2 emissions and output equal to 1.50. A moderately high

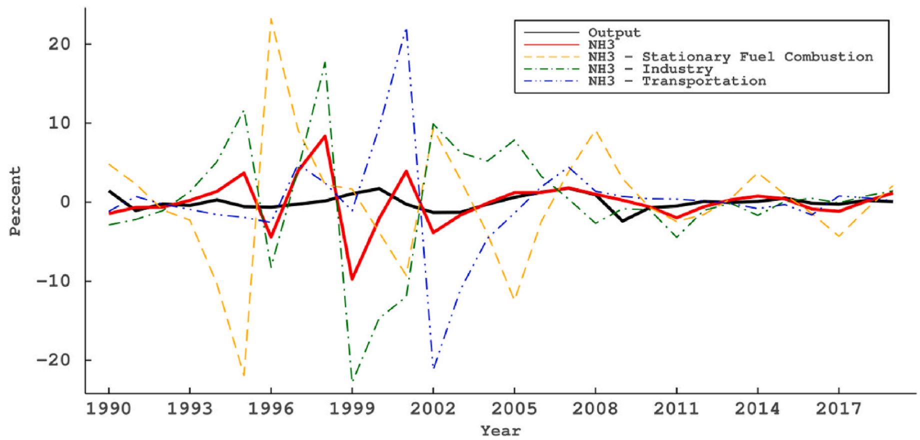

Fig. 9. Ammonia vs GDP.

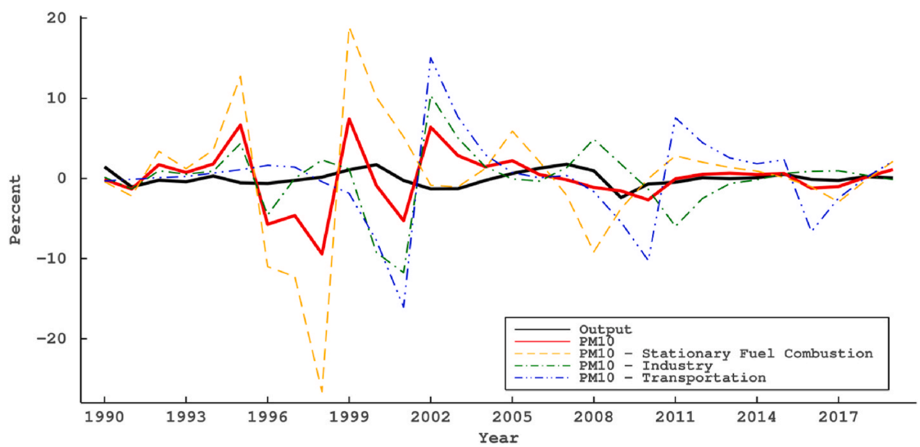

Fig. 10. Particulate Matter 10 vs GDP.

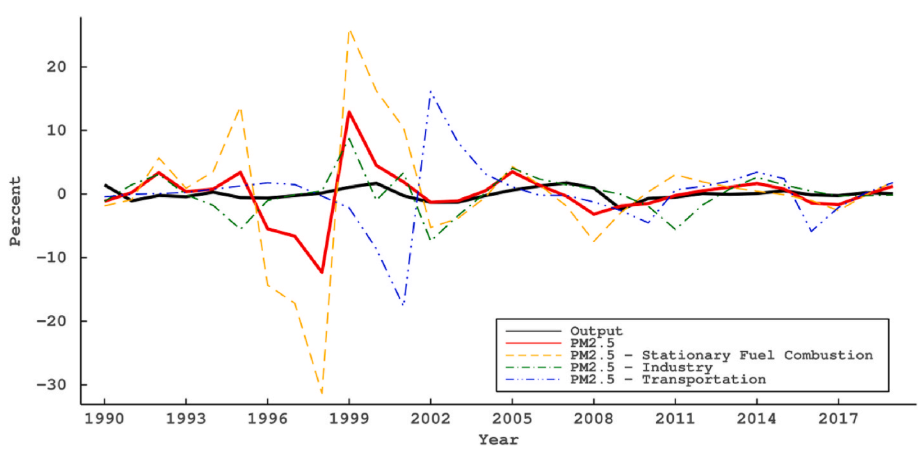

Fig. 11. Particulate Matter 2.5 vs GDP.

contemporaneous correlation (0.63) is registered between carbon dioxide emissions and the business cycle. This result is in line with those found by Heutel (2012) and Doda (2014), both of them suggesting procyclicality between the production process and CO_2 emissions.

Going further with the analysis of atmospheric carbon compounds, it emerges that *CO* emissions are in general more volatile than output. This is particularly true for *CO* emissions from stationary fuel combustion and industry sources, whose standard deviations are more than 5 times that of real GDP. These features can be evinced also by inspecting the series framed by Fig. 5. Aggregate *CO* emissions are moderately procyclical with the business cycle (0.67). The same considerations hold true for *CO* emissions from transportation (0.68). On the contrary, those

Table 1
Stylized facts: GDP, fossil energy use and atmospheric pollutants for the US economy.

Variable	$\sigma(x_t)$	$\sigma(x_t)/\sigma(y_t)$	$\rho(y_t, x_{t-2})$	$\rho(y_t, x_{t-1})$	$\rho(x_t, y_t)$	$\rho(y_t, x_{t+1})$	$\rho(y_t, x_{t+2})$
Output	0.92	1.00	−0.18	0.29	1.00	0.29	−0.18
Fossil Energy Use	1.28	1.38	−0.22	−0.08	0.66	0.18	−0.10
Coal	2.77	3.00	−0.10	−0.07	0.39	0.08	−0.06
Gas	1.63	1.76	0.03	−0.02	0.20	−0.27	−0.26
Oil	1.30	1.41	−0.31	−0.09	0.77	0.50	0.05
$\mathbf{CO_2}$	1.39	1.50	−0.18	−0.07	0.63	0.16	−0.10
CO	2.28	2.47	−0.32	0.25	0.67	0.23	−0.13
CO Stationary Fuel Combustion	5.59	6.06	−0.09	−0.16	−0.11	0.13	−0.05
CO Industry	5.29	5.73	−0.18	−0.01	0.13	0.37	0.39
CO Transportation	2.58	2.80	−0.28	0.27	0.68	0.17	−0.18
$\mathbf{NO_x}$	2.16	2.34	−0.13	−0.34	−0.16	0.05	0.30
NO_x Stationary Fuel Combustion	1.77	1.92	0.09	0.29	0.26	0.10	0.04
NO_x Industry	2.64	2.86	−0.36	−0.60	−0.10	0.21	0.57
NO_x Transportation	3.54	3.84	−0.10	−0.37	−0.22	−0.00	0.23
$\mathbf{SO_2}$	4.25	4.61	−0.06	0.04	0.19	0.25	0.13
SO_2 Stationary Fuel Combustion	4.88	5.28	−0.05	0.05	0.20	0.24	0.11
SO_2 Industry	4.07	4.41	−0.01	0.39	0.39	−0,03	−0.21
SO_2 Transportation	8.33	9.02	−0.27	−0.32	−0.34	0.27	0.45
VOC	1.70	1.84	−0.27	−0.10	0.04	0.08	−0.10
VOC Stationary Fuel Combustion	8.07	8.74	0.13	−0.47	−0.58	−0.24	0.11
VOC Industry	2.73	2.95	−0.25	−0.03	−0.06	0.05	0.03
VOC Transportation	2.02	2.19	−0.30	0.10	0.53	0.29	−0.27
$\mathbf{NH_3}$	3.06	3.31	−0.09	0.15	0.00	−0.04	0.17
NH_3 Stationary Fuel Combustion	7.84	8.49	0.29	−0.03	−0.09	−0.13	−0.02
NH_3 Industry	7.72	8.36	−0.15	−0.29	−0.28	0.04	0.46
NH_3 Transportation	6.57	7.12	0.01	0.46	0.34	0.02	−0.28
$\mathbf{PM_{10}}$	3.48	3.77	−0.06	−0.09	0.03	0.06	−0.11
PM_{10} Stationary Fuel Combustion	7.95	8.61	−0.10	0.06	0.19	0.10	−0.29
PM_{10} Industry	4.09	4.42	0.20	−0.19	−0.22	−0.06	0.21
PM_{10} Transportation	5.59	6.05	−0.31	−0.33	−0.16	0.10	0.26
$\mathbf{PM_{2.5}}$	4.09	4.43	−0.05	0.13	0.27	0.20	−0.27
$PM_{2.5}$ Stationary Fuel Combustion	10.06	10.90	−0.03	0.17	0.24	0.06	−0.37
$PM_{2.5}$ Industry	3.08	3.34	0.05	0.29	0.41	0.44	0.04
$PM_{2.5}$ Transportation	5.35	5.80	−0.12	−0.41	−0.26	0.07	0.30

Notes: All data are in logarithms, HP-filtered, and multiplied by 100 to express them in percentage deviation from trend.

emissions which originate from stationary fuel combustion and industry sources appear to be characterized by an acyclical behaviour with respect to real output.

The mutual interactions between NO_x emissions and the business cycle can be first investigated by inspecting Fig. 6. All series, from the main aggregate to its components, appear to be relatively more volatile than output. In particular, as shown by Table 1, those NO_x emissions which originate from the transportation sector are 3.84 times as volatile as real GDP. The contemporaneous cross-correlation with output is very weak for all NO_x emissions. NO_x emissions from industrial sources show a peculiar behaviour, in that they seem to negatively lead the business cycle by one year (−0.60) and positively lag it by two years (0.57).

Independent of their level of aggregation, all cyclical components of SO_2 emissions are more volatile than real output. This is what visually stands out when comparing sulfur dioxides and real GDP by means of Fig. 7. These results are corroborated by the relative standard deviations presented in Table 1. All sulfur dioxide emissions result to be at least 4 times as volatile as the business cycle. SO_2 emissions from transportation, in particular, are characterized by a standard deviation about 9 times that of output. The analysis of the cross-correlations does not highlights relevant patterns between SO_2 and the business cycle. All coefficients, independent of the lead/lag and the sign, are in general relatively low, thereby signalling overall weak levels of association.

From a quick inspection of Fig. 8, it emerges that volatile organic compounds from stationary fuel combustion are much more volatile than output. Indeed, Table 1 shows that they are characterized by a standard deviation more than 8 times that of real GDP. The main aggregate and the other components, on the other hand, are less volatile. While the main aggregate results to be essentially uncorrelated with the business cycle, this does not hold for some of its components. More specifically, volatile organic compounds from stationary fuel combustion appear to be mildly countercyclical (−0.58). Those from transportation, on the contrary, display a moderate procyclical behaviour with the business cycle (0.53).

Ammonia emissions are characterized by high volatility and low association with the cycle. As portrayed by Fig. 9, NH_3 is clearly more volatile than the business cycle. Excluding the main aggregate, Table 1 shows that all components are at least 7 times more volatile than output. On the other hand, their degree of co-movement with the business cycle is relatively low. All cross-correlations, irrespective of their lead/lag relationships, are lower than 0.5 in absolute value, thereby leading to the conclusion that NH_3 emissions and the overall business cycle are characterized by very low levels of association.

The cyclical behaviours of particulate matter, PM_{10} and $PM_{2.5}$ are studied jointly by means of Figs. 10 and 11, respectively. In both cases, the main aggregate as well as the components appear to be more volatile than the business cycle. To give an example, Table 1 shows that $PM_{2.5}$ linked to stationary fuel combustion are almost 11 times more volatile than real output. This value represents the highest relative volatility of the dataset. In general, the low values of cross-correlations suggest that particulate matter is weakly correlated with the business cycle. In particular, all PM_{10} are acyclical with values approaching 0. The maximum value of cross-correlation (0.44) at $n = 1$ suggests that $PM_{2.5}$ emissions from the industry sector lag real output by one year; the degree of association, however, is relatively weak.

5. Conclusions

This work aims at identifying co-movements between specific series concerning the use of fossil energy, anthropogenic air pollution and the aggregate business cycle. GHG emissions, air pollutants and energy consumption fall along the environmental dimension of the ESG framework (Li et al., 2021) and, in this study, are analysed though a macroeconomic lens.

The nature of this exploratory work is essentially descriptive. Its final goal is to organize meaningful information in the form of stylized facts that describe the salient features of economic fluctuations, fossil energy use and the subsequent emissions of gaseous wastes. Furthermore, given the recent emphasis on environmental matters, this analysis also aims to endow the theoretical macroeconomist with a set of rough "numbers" which can be used to ascertain how well theoretical models are able to replicate empirical patterns.

The first result that emerges from this descriptive analysis is the large volatility which characterizes all non-economic series. This feature appears more marked for those variables pertaining to the realm of air pollutants. Among the reasons that can be advanced to qualify this behaviour is the different intrinsic nature of the series: purely economic in the case of the business cycle and techno-physical for the series concerning fossil energy use and atmospheric pollutants.

Focusing on co-movements, not all variables seem to be correlated with the business cycle. In the case of fossil energy, the main aggregate and oil use are moderately highly procyclical. Oil use, in particular, is the variable which shows the highest contemporaneous cross-correlation with real output. Among air pollutants, carbon monoxide and carbon dioxide emissions are those characterized by the highest procyclicality. Volatile organic compounds from stationary fuel combustion are mildly countercyclical; those from transportation, on the contrary, are weakly procyclical. The behaviour of nitrogen oxides from industry, negatively leading the cycle by one year and positively lagging it by two years, is also noteworthy. All other series are essentially only weakly related to the business cycle.

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Declaration of competing interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All sources and links to access the original data used in the article are supplied in the Appendix

Appendix

Hereafter the list of series employed throughout this work and the sources supplying them.

I ***Implicit Price Deflator*** [index 2012 = 100, annual] is available from Federal Reserve Economic Data (FRED). (https://fred.stlouisfed.org/series/A191RD3A086NBEA);
II ***Nominal Output*** [billions of dollars, annual] is available from Federal Reserve Economic Data (FRED). (https://fred.stlouisfed.org/series/GDPA);
III ***Fossil Energy Consumption***, ***Coal Consumption***, ***Gas Consumption***, and ***Oil Consumption*** [quadrillion btu, annual] are available from U.S. Energy Information Administration (EIA). (https://www.eia.gov/totalenergy/data/browser/xls.php?tbl=T01.03&freq=m);
IV ***CO_2 emissions*** [giga tons of carbon, annual] are available from U.S. Energy Information Administration (EIA). (https://www.eia.gov/totalenergy/data/browser/xls.php?tbl=T11.01&freq=m);
V ***CO***, ***NO_x***, ***SO_2***, ***VOC***, ***NH_3***, ***PM_{10}***, and ***$PM_{2.5}$*** emissions [thousands of tons, annual] are available from U.S. Environmental Protection Agency (EPA). (https://www.epa.gov/sites/default/files/2021-03/national_tier1_caps.xlsx).

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